Large scale extragalactic jets powered by very-high energy gamma rays

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The radiative cooling of electrons responsible for the nonthermal synchrotron emission of large scale jets of radiogalaxies and quasars requires quasi continuous (in time and space) production of relativistic electrons throughout the jets over the scales exceeding 100 kpc. While in the standard paradigm of large scale jets this implies *in situ* acceleration of electrons, in this letter we propose a principally different "non-acceleration" origin of these electrons, assuming that they are implemented all over the length of the jet through effective development of electromagnetic cascades initiated by extremely high energy γ-rays injected into the jet from the central object. This scenario provides a natural and very economic way to power the jets up to distances of 100 kpc and beyond.

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Although there is little doubt in nonthermal origin of radiation of large scale extragalactic jets, it remains a theoretical challenge to explain how the relativistic electrons responsible for the radio-to-X-ray synchrotron emission could be distributed quite uniformly all over the huge length of the jet $L_{jet} \sim 100$ kpc. Although the recent exciting discoveries by the Chandra observatory added much to our knowledge of structures of these fascinating components of powerful radiogalaxies and quasars, they didn't solve the old problems and, if fact, brought new puzzles. In particular, there remain yet substantial problems concerning the identification of the X-ray emission mechanism. The most natural mechanism, the synchrotron radiation of multi-TeV electrons, applied in a standard manner to large scale jets, faces certain difficulties to interpret the observed X-ray features of a significant fraction of the Chandra jets (see e.g. Ref [1]). Therefore the recent "trend" which invokes relativistic bulk motion with Lorentz factor as large as $\Gamma \sim 10$ (on ≥ 100 kpc scales !), and thus increases significantly the efficiency of the inverse Compton scattering on 2.7 K cosmic background radiation (CMBR) as a source of X-rays [2,3], was readily accepted by the extragalactic jet community [1]. The very idea of relativistic bulk motion could be very productive also for other possible jet models [4]. In particular, it would allow explanation of the broad-band data of the jet of 3C 273 by a single population of electrons [5]. Even so, this effect does not solve the problem of continuous (in space and time) acceleration of multi-TeV electrons. The association of the observed X-rays to very high-energy (VHE) protons could be a possible solution [4].

In this letter we suggest a "non-acceleration" version of the electron synchrotron model, namely assuming that electrons *are not accelerated* in the jet, but are result of pair production of extremely high energy γ-rays interacting with the CMBR . The pair production in the field of CMBR and diffuse infrared background photons as a source of ultra-relativistic electrons created far from the central object (AGN) has been suggested [6] in the context of formation of giant extragalactic pair halos. The same process can provide ultrarelativistic electrons for nonthermal synchrotron X- and γ-rays in clusters of galaxies and beyond [4]. Recently, highly collimated neutral beams (neutrons and γ-rays) have been noticed as possible supplier of synchrotron-emitting electrons in the extended jets of FRII radio galaxies [5,7].

The mean free path of γ-rays in the field of CMBR has a minimum $L_\gamma \approx 8$ kpc at $E_\gamma \simeq 10^{15}$ eV. At both lower and higher energies L_γ increases – sharply (exponentially) at $E_\gamma \ll 10^{15}$ eV (due to the threshold effect γ-rays interact with the Wien tail of CMBR), and slowly, $L_\gamma \approx 14.6\ E_{\gamma,16} T_{2.7}^{-2}[1 + 0.7 \ln\ (E_{\gamma,16}T_{2.7})]^{-1}$ kpc at $E_\gamma \gg 10^{15}$ eV due to the decrease of the cross-section with the parameter $E_\gamma E_{\rm CMBR} \gg m_{\rm e}^2c^4$. Hereafter, $E_{\gamma,16} = E_\gamma/10^{16}$ eV, $T_{2.7} = T/2.7$ K. Thus, a γ-ray beam with a broad spectrum extending to 10^{18} eV can supply the jet with "desirable" VHE electrons along the jet, and thus power the jet up to distances ~ 100 kpc or even more.

In what follows we analyze a simple model in which a VHE photons are injected into a cylindrical jet and, interacting with CMBR as well as with the low-frequency radiation of the jet itself, initiate an electromagnetic cascade, the relevant processes being pair-production (PP), inverse Compton scattering (ICS) and synchrotron radiation (see Fig. 1). For numerical calculations we use the code described in Ref. [8] which solves kinetic equations for VHE particles cascading on soft photon backgrounds.

The first generation of pair-produced electrons upscatter the soft background photons. Propagation length of electron with respect to ICS in Klein-Nishina regime is $L_{e,\rm KN} \approx 1.5\, T_{2.7}^{-2} E_{e,16}$ kpc. The electrons suffer also synchrotron losses.

High resolution radio observations show that the magnetic field in large scale jets may dominate by the regular

component parallel to the jet axis, although there could be anomalous regions near the knots with oblique field components (see e.g. Ref. [9]). Here we adopt a simplified picture assuming that the field consists of two - random and regular (aligned with the jet axis) - components, and that the regular component significantly exceeds the random component. We normalize these fields as $B_0 = B_{0,-5} \times 10^{-5}$ G and $B_r \sim 0.01 B_0 = B_{\mathrm{r},-7} \times 10^{-7}$ G, respectively. Generally, if the first generation electrons appear at small angle to the regular magnetic field (i.e. the γ-ray beam from the central engine is directed along the jet), they will spiral with a small pitch angle θ in the magnetic field B_0 and at the same time get gradually deflected by the random magnetic field B_{r}. As long as the deflection of electrons does not exceed a few degree, the synchrotron losses of electrons are dominated by the random magnetic field. At larger angles the synchrotron radiation in the regular field becomes more important. Moreover, for $\theta \geq 30°$ the latter dominates also over the Compton losses. At the same time, because of the Klein-Nishina effect, the electrons of extremely high energies, $E \geq 10^{17}$ eV are basically cooled through the synchrotron radiation, even when they move at small pitch angles.

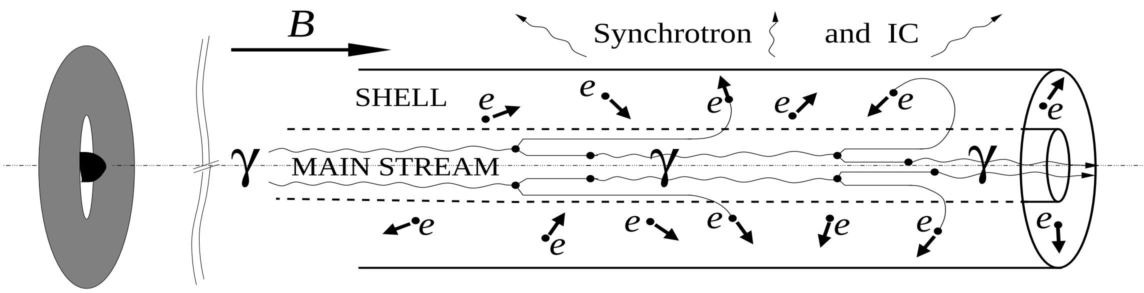

FIG. 1. Extremely high energy gamma-rays, $E \gg 10^{14}$ eV, from central engine form the “main stream” of the jet and provide VHE electrons throughout the entire jet. The low energy electrons below the critical energy E_{crit} escape the “main stream” and form a “shell” of the jet. Distant observer see the synchrotron and inverse Compton radiation from electrons in the ”shell”.

Deflection of electrons in the jet can be approximately described as diffusion in pitch angle [10,11]. The diffusion length L_{diff} can be estimated as [11] $L_{\mathrm{diff}} \approx 5\ B_{\mathrm{r},-7}^{-2} E_{e,14}^{2} l_{\mathrm{pc}}^{-1} (\theta_0/3°)^{-2}$ kpc , where l_{pc} is the correlation length of the random B-field in parsecs and θ_0 is the initial opening angle of the primary photon beam. When electrons cool down to $\sim 10^{14}$ eV, their propagation length is determined by ICS $L_e = 0.3(T_{2.7})^{-4}(E_{e,14})^{-1}$ kpc . When L_{diff} becomes of order of L_e the cascade electrons are essentially deflected by the random B-field. Comparing the diffusion length to the propagation elngth we find that the electron trajectories below the energy $E_{\mathrm{crit}} = 4 \times 10^{13} B_{\mathrm{r},-7}^{2/3} l_{\mathrm{pc}}^{1/3} T_{2.7}^{-4/3} (\theta_0/3°)^{2/3}$ eV are randomized. Such electrons are cooled through synchrotron and ICS losses, and form a bright ”shell” around the ”main stream” of the cascade as it is demonstrated in Fig. 1.

The energy losses of ”shell” electrons are dominated by the regular magnetic field which establish a standard $dn_e/dE_e \propto E_e^{-2}$ type spectrum of electrons. Correspondingly, the spectrum of synchrotron radiation behaves as $\nu F_\nu \propto \nu^{0.5}$ with a maximum at $h\nu_{\mathrm{max}} = 1.6\ B_{0,-5}(E_{\mathrm{crit}}/10^{14}\ \mathrm{eV})^2$ keV . Note that at low ener-

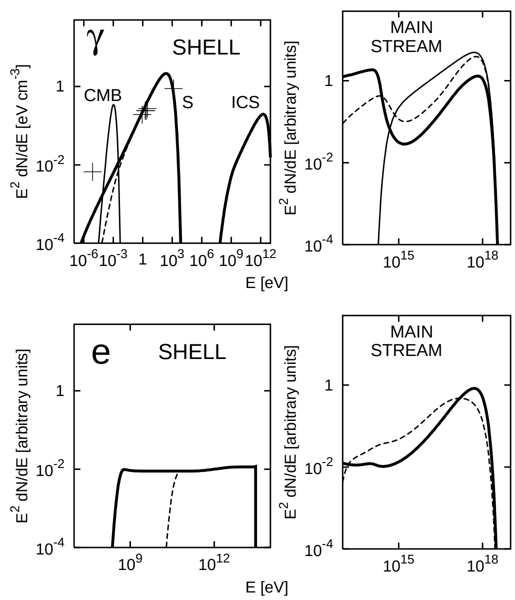

FIG. 2. Evolution of energy spectra of γ-rays (upper panel) and electrons (lower panel) in the “main stream” (right) and in the ”shell” (left) of the jet. Upper panel (right): thin line – initial photons (at the base of the jet), dashed lines – after 50 kpc, thick lines – 500 kpc. Upper panel (left): the synchrotron/ICS spectra of the ”shell” (dashed line – after 10^6 yr, thick solid line – after 10^8 yr). For comparison the experimental points of the knot A of the quasar 3C 273 [12] are also shown, assuming the knot size 1 kpc. The CMBR background is shown by the thin solid line. Lower panel: evolution of electron spectra in the ”main stream” and in the ”shell” (notations are the same as in the upper panel).

gies a possible energy dependent-escape might make the electron spectrum, and subsequently the synchrotron radio spectrum somewhat steeper.

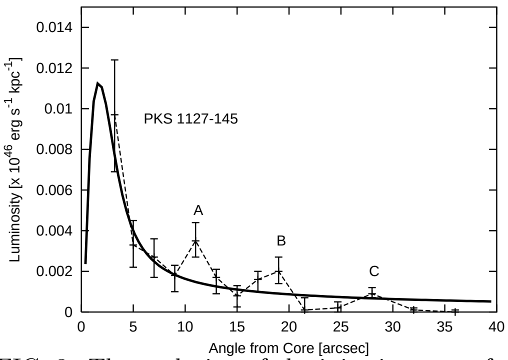

FIG. 3. The evolution of the injection rate of the cascade electrons with energy $E \leq E_{\rm crit} = 3 \times 10^{13}$ eV to the "shell". For comparison, the angular distribution of the X-ray luminosity of the jet in the quasar PKS 1127-145 [13] is shown. Primary spectrum of γ-rays was taken as power-law $E^{-1.5}$ with a cutoff at 10^{18} eV. Luminosity of the primary γ-ray beam is 10^{46} erg/s. Total luminosity of electrons in the shell is 10 % of the primary beam luminosity.

Because the spectra of Chandra jets typically extend beyond 1 keV, for a reasonable value of $E_{\rm crit} \sim 10^{14}$ eV, which is a free parameter in our model, the regular B-field should exceed 10^{-5} G. This explains the need in the regular field in our model. We need sufficiently strong magnetic filed in order to explain the X-ray data. The random field cannot play this role because such a strong random field would destroy the cascade from very beginning. On the other hand we need a cascade in order to have a more or less homogeneous distribution of electrons, both in density and energy spectrum, across the jet. Assuming that the maximum energy of synchrotron radiation from the jet lies in the X-ray energy domain, which minimizes the energy requirement to the source, we find the following relation between the random and regular magnetic fields: $B_{{\rm r},-7}^2 B_{0,-5}^{3/2} l_{\rm pc} \approx 7 T_{2.7}^4 (\theta_0/3^o)^{-2} \left(h\nu_{\rm max}/\,1{\rm keV}\right)^{3/2}$. An example of numerical calculation of evolution of photon and electron spectra in the "main stream" and in the "shell" are shown in Fig. 2.

So far we have assumed that the synchrotron background in the jet is negligible compared to the external CMBR background. This seems to be the case for the jet in PKS 1127-145 (see Fig. 3) because the radio power of the jet is small [13]. However, as one can see from Fig. 2, the densities of CMBR and synchrotron photons can be of the same order, as, for example in the knot A of the jet in 3C 273 [12]. Therefore, the interactions of the highest energy γ-rays with the radio synchrotron radiation may well dominate, at least in the bright knots. Besides, the random B-field in the knots can be stronger than in the rest of the jet, which would result in increase of $E_{\rm crit}$ at which the electron trajectories are randomized. To demonstrate this effect we performed numerical calculations assuming very hard γ-ray spectrum with energy concentrated around 10^{17} eV. In Fig. 4 we show the evolution of rate of production of electrons in the knot, which determines the synchrotron luminosity of the "shell", together with the profile of the synchrotron X-radiation radiation measured by Chandra.

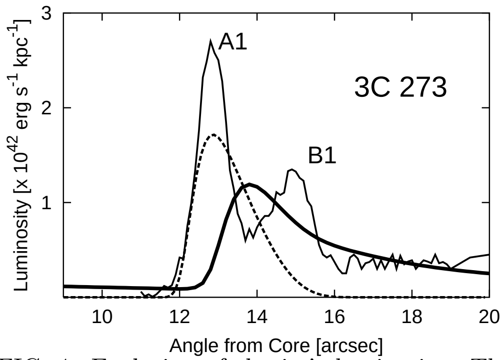

FIG. 4. Evolution of the jet's luminosity. The thin solid line represents X-ray data for 3C 273 [12], the dashed line is intensity profile of the synchrotron background used in numerical calculation. Thick solid line is the injection rate of electrons with energy $E \leq E{\rm crit} = 10^{14}$ eV from the "main stream" of the electromagnetic cascade, i.e. the rate of "visible" electrons injected in the jet "shell". For the primary spectrum of γ-rays we assumed $E^{-1.5}$ with exponential cut off at 10^{19} eV, which allows to avoid the large energy release at small distances. Luminosity of the primary photon beam is 10^{44} erg/s.

One can see that in the initial part of the jet, where synchrotron background is quite low, the rate of injection of the photoproduced electrons into the "shell" is small. But in the knot A the rate increases rapidly. An observer who detects the jet from a side and does not see the "main stream" of the cascade, may conclude that electrons are effectively accelerated in the knot.

Apparently, the formation of knots in the suggested model is a nonlinear process. The increase of synchrotron luminosity at some point of the jet would lead to an increase of the rate of ejection of electrons from the "main stream". This, in its turn leads to the further increase of synchrotron luminosity and formation of bright knots. Note that although the radio luminosity of the jet is directly related to the injection rate of electrons in the "shell", and therefore to the VHE γ-ray luminosity of the central source, it depends on some other factors as well, like the time of "operation" of the central source, the strength of the magnetic field in the jet, the escape of electrons from the jet, etc. While the X-ray data tell us about the VHE γ-ray luminosity of the central source at the *present epoch*, the radio data rather reflect the history of evolution of the the central source. An important question is whether photons with energies larger than 10^{16} eV can be *effectively produced* and at the same time *freely escape* the dense photon environments in the central engines of AGN which are believed to be powerful particle accelerators up to $E_{\rm max} \geq 10^{19}$ eV [14].

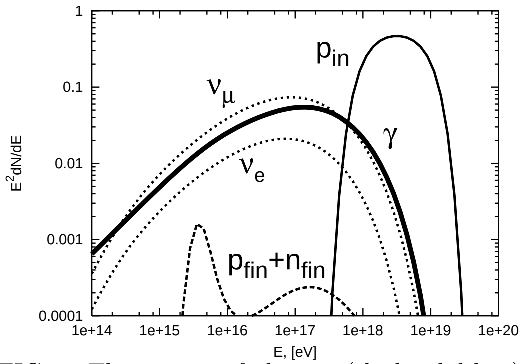

FIG. 5. The spectra of photons (thick solid line), nucleons (dashed line) and neutrinos (dotted lines) after they escape the region of proton accelerator close to the base of the jet. The initial proton spectrum is shown by the thin solid line. It is assumed that a beam of protons is injected to the region of size 10^{15} cm filled with blackbody radiation with temperature 10^4 K. Total energy emitted in the VHE γ-ray beam is 27 % of the energy contained in the primary photon beam normalized to $\int(Edn/dE)dE = 1$.

The accelerated protons can produce VHE γ-rays interacting with the ambient photon fields (supplied, for example by accretion disk around the massive black hole) through photo-meson process. Since we need a *beamed* γ-radiation emitted at a small angle to the MHD jet, the protons should cross the photon field almost rectilinearly. Therefore, the condition of a high *proton-to-gamma* conversion efficiency in the production region of a linear size R implies $\tau_{p\gamma} = \sigma_{p\gamma}R\ n_{\rm ph} \geq 1$. On the other hand, the produced γ-rays can effectively escape the production region if $\tau_{\gamma\gamma} = \sigma_{\gamma\gamma}R\ n_{\rm ph} < 1$. Thus, the production region can freely escape only those γ-rays for which $\sigma_{\gamma\gamma} < \sigma_{p\gamma}$. This is possible for very energetic γ-rays in a "hot" ambient photon gas. As an example, we show in Fig. 5 the spectra of protons and γ-rays emerging from a source filled with thermal radiation with $T = 10^4$ K which serves a target for protons within a narrow energy interval between $\sim 10^{18}$ and 10^{19} eV. Since the center of mass energy of $\gamma\gamma$ interaction significantly exeeds the threshold of pair production, $(E{\rm kT})/m_{\rm e}^2c^4 \sim 10^6E_{17}$, at $E \geq 10^{17}$ eV the pair-production cross-section becomes less than the (almost energy-independent) photo-meson production cross-section, $\sigma_{p\gamma} \simeq 10^{-28}$ cm^2. Therefore the $E \geq 10^{17}$ eV γ-rays are not only effectively produced, but also are able to escape the source without significant losses. The numerical calculations shown in Fig. 5 illustrate this possibility. Note that a broader, e.g. power-law type proton spectrum would result in effective production of less energetic, $E \leq 10^{16}$eV γ-rays as well. However, due to the increase of the $\gamma\gamma$ cross-section, only a small fraction of these photons can escape the source.

To conclude, the electromagnetic cascade initiated by VHE photons interacting with ambient radiation fields in the large scale extragalactic jets is an attractive mechanism for production of ultra-relativistic electrons (with almost 100 percent efficiency) which can be responsible for the observed radio-to-X-ray spectra of jets. The trajectories of electrons with energies below $E_{\rm crit}$ are isotropized by the random magnetic field B_r. Such electrons form a "shell" around the cascade. Observer, who looks at the jet from a side, sees synchrotron and inverse Compton radiation only form the "shell" electrons. The cascade can be developed effectively in the jet provided that the strength of the random B-field does not exceed 1 μG. On the other hand, when at a very large distances from the central source the random field is reduced to a very low level comparable with the intergalactic field, $B \sim 10^{-9}$ eV or less, the cascade continues almost rectilinearly until the 10-100 TeV γ-rays start to interact effectively with the diffuse infrared background photons. This interactions would lead to the formation of *observable* giant pair halos with specific angular and energy distributions depending on the intensity of diffuse infrared background at the cosmological epoch corresponding to the redshift of the central source z [6]. And finally, if the central source is a blazar, i.e. the jet is pointed to the observer, we may expect beamed γ-ray emission with a characteristic for cascades $E^{-1.5}$ type spectrum extending to 100 TeV. However, due to significant intergalactic absorption, the γ-rays will arrive with significantly distorted spectra. The possible implications of this mechanism for the TeV blazars like Mkn 421 and Mkn 501 are discussed elsewhere.

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